Performance properties of rubberized stone matrix asphalt mixtures produced through different processes

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Performance properties of rubberized stone matrix asphalt mixtures produced through different processes

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HIGHLIGHTS

- The introduction processes of CRM (dry process and wet process) may have effect on the high temperature dynamic modulus and rutting resistance, while no significant influence on the moisture susceptibility and fatigue life.
- The use of combination of SBS and CRM in the terminal SMA significantly improved the resistance to rutting and fatigue cracking.

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ABSTRACT

The study investigated the dynamic modulus, rutting resistance, moisture susceptibility and fatigue resistance of rubberized Stone Matrix Asphalt (SMA) through laboratory performance tests. Rubberized SMA mixes were produced by three processes: the dry process, the wet process and the terminal in the laboratory. For comparison purposes, SMA mixtures containing styrene–butadiene–styrene (SBS) modified binder and virgin asphalt of PG 67-22 were also evaluated and compared to rubberized SMA. Dynamic modulus and direct tension fatigue tests were performed using the Asphalt Mixture Performance Tester (AMPT) system. Rutting resistance and moisture susceptibility were analyzed by Hamburg wheel tracking test using asphalt pavement analyzer (APA). The results showed that: (1) the incorporation of CRM improved the high temperature dynamic modulus, the resistance to rutting and fatigue life of SMA mixes. (2) The introduction processes of CRM (dry process and wet process) may have effect on the high temperature dynamic modulus and rutting resistance, while no significant influence on the moisture susceptibility and fatigue life. (3) The use of combination of SBS and CRM in the terminal SMA significantly improved the resistance to rutting and fatigue cracking. (4) The rubberized SMA with 10% CRM had the lower performance properties than SBS SMA, regardless of the dry process or the wet process.

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1. Introduction

Crumb rubber modifier (CRM) is introduced into asphalt mixtures by the three general processes: the dry process, the wet process and the terminal blend. In the typical dry process, CRM, generally considered to be an aggregate replacement in the mix rather than a binder additive, is mixed directly with aggregate in the drum at the mixture production plant. In the wet process, CRM, considered as the asphalt binder modifier, is field blended with asphalt binder in a mixing tank at high temperature (170–205 °C) for 45–60 min. For the terminal blend, CRM and polymers (i.e. styrene–butadiene–styrene (SBS)) are used to produce the rubberized binders at a supplier's terminal, which can be shipped to the mixture production plant and stored in the plant's binder storage tanks, like SBS modified asphalt binder [1].

Different processes may result in the different performance properties of the rubberized mixtures. Rubberized mixtures in the wet process or at the terminal blend exhibited the similar or better performance properties compared to the control asphalt mixtures [2–7]. The dry process has the inconsistent field performance with service life varying from two to twenty years, depending on the CRM type and content as well as the construction method [8]. However, the dry process is easier and more economic for a manufacturer to produce the rubberized mix since it needs neither the mixing tanks nor the terminal equipment.

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A modified dry process was used in Stone Matrix Asphalt (SMA) in Georgia since 2008: smaller size (30 or 40 mesh) and lower content of CRM (about 10% mass of asphalt binder) as well as a cross-link agent (transpolyoctenamer (TOR) polymer) were used to produce rubberized SMA. The field performance showed that rubberized SMA pavement in this dry process exhibited good conditions after three years in service [9,10]. However, it is unclear whether the rubberized SMA in this dry process has the similar performance to the wet process and the terminal blend, although the dry process is more economic.

2. Objectives

Since the introduction processes of CRM into the asphalt mixes have significant effect on the performance properties of the rubberized mixes, it is necessary to investigate the performance differences of the three rubberized mixtures so that agencies can make a better choice on the process types that will perform best for their desired application. The objectives of the study are to investigate the performance properties of rubberized SMA mixes and to explore the influence of the introduction methods of CRM (the dry process and the wet process) on the performance characteristics of SMA mixes.

3. Scope

In this study, the three rubberized SMA mixes were produced by three processes: the dry process, the wet process and the terminal blend in the laboratory. For comparison purposes, SMA mixtures containing SBS modified binder and virgin asphalt of PG 67-22 were also used. Optimum asphalt contents (OAC) of the above five SMA mixtures were designed according to the specification of Georgia department of transportation (GDT 123). The performance properties of the five SMA mixes were evaluated in terms of dynamic modulus, rutting resistance, moisture susceptibility and fatigue resistance. Dynamic modulus and direct tension fatigue tests were performed using the Asphalt Mixture Performance Tester (AMPT) system. Rutting resistance and moisture susceptibility were analyzed by Hamburg wheel tracking test using asphalt pavement analyzer (APA).

4. Experimental

4.1. Materials and sample preparing

Five SMA mixtures were produced using five asphalt binders: virgin asphalt of PG 67-22 (noted as virgin SMA), rubberized binder in the dry process (noted as dry process SMA), rubberized binder in the wet process (noted as wet process SMA), terminal blend binder (noted as terminal SMA) and SBS modified binder (noted as SBS SMA). −30 mesh ambient CRM at 10% of the weight of the asphalt binder was used in rubberized SMA pavement in Georgia. Based on the CRM engineering application in Georgia, the wet process rubberized binder was produced by mixing 10% −30 mesh ambient CRM with a virgin binder of PG 67-22 at 170 °C and 700 RMP for 45 min in the laboratory. The dry process binder used the same CRM and virgin binder, which were introduced into aggregates together with a cross-link agent – TOR polymer at 4.5% of the weight of the CRM.

To avoid excessive drain-down, cellulose fiber at 0.35% by the weight of the total mixture was added to all mixes. For anti-stripping purposes, hydrated lime at 1.0% by the weight of the total aggregate was used in all mixes. The gradation of 12.5-mm SMA showed in Table 1 were designed in accordance with Georgia's mix design procedure [11], and optimum asphalt content (OAC) of SMA mixtures were designed according to the specification of SMA design (GDT 123). Table 2 presents OAC of SMA mixtures.

Table 1
Aggregate gradation of SMA.

Sieve (in.)	3/4	1/2	3/8	No. 4	No. 8	No. 200
Percentage passing (%)	100.0	90.7	61.7	27.0	17.8	10.0

Table 2
Optimum asphalt content of SMA mixture.

SMA mix type	Virgin	Dry process	Wet process	Terminal	SBS
OAC (%)	6.3	6.3	6.9	6.4	6.3

Mixture specimens were prepared in the following ways. The loose mixtures were aged in a forced-draft oven for 2 h ± 5 min at a compacted temperature before compaction to simulate the short-aging during the mixing and construction, and then the aged loose mixtures were compacted by a Superpave gyratory compactor (SGC). The SGC compacted samples were then cored/cut to the specified sizes for the dynamic modulus test, the direct tension fatigue test and APA Hamburg wheel tracking test. The sample dimensions and the target air voids are presented in Table 3.

5. Test method

5.1. Dynamic modulus (E^*) test

Dynamic modulus tests were conducted to measure the linear viscoelastic (LVE) behavior of SMA mixtures. Dynamic modulus tests were performed in load-controlled and axial compression mode using AMPT. In this test, the strain amplitudes were controlled below 115 micro strains to ensure the specimen response was within a linear viscoelastic limit. Three replicate specimens at a target air void level were tested at three temperatures (4 °C, 20 °C, 45 °C) and four loading frequencies (0.01 Hz, 0.1 Hz, 1 Hz, 10 Hz) according to the AASHTO 13 TP79-12 requirement. Prior to E^* testing, the specimens were conditioned in an environmental chamber to reach the test temperature stipulated in AASHTO 13 TP79-12. Conditioning times for the E^* test at 4 °C, 20 °C, and 45 °C were 18 h, 3 h, and 3 h, respectively.

5.2. Direct tension fatigue test

The S-VECD model is based on the elastic–viscoelastic correspondence principle, the work potential theory, and the temperature–time superposition principle. The S-VECD direct tension fatigue tests were performed to characterize fatigue performance of SMA mixtures at 17 °C and a frequency of 10 Hz using an AMPT [12]. Three to four replicate specimens at a target air void were measured at three to four different strain amplitudes (high, medium and low) to produce a wide range of N_f (from 1000 to 100,000) [13]. Prior to the direct tension fatigue test, the samples were glued to two end platens using a steel epoxy and a special gluing jig was used to eliminate eccentricity, and then the specimens were conditioned in an environmental chamber for 3 h to reach the test temperature. The data from the direct tension fatigue test were analyzed by the simplified viscoelastic continuum damage (S-VECD) theory using the fatigue analysis software developed by Underwood and Kim and G^R (the rate of change of the averaged released pseudo strain energy values) failure criterion was used in the fatigue life prediction of SMA mixtures [12].

5.3. Hamburg wheel tracking test

The Hamburg wheel tracking test was conducted to investigate SMA's resistance to moisture damage and rutting using APA in

Table 3
Sample dimensions and target air voids.

Test type	Diameter × height	Target air void
Dynamic modulus test	100 mm × 150 mm	5.0 ± 0.5%
Direct tension fatigue test	100 mm × 130 mm	5.0 ± 0.5%
Hamburg wheel tracking test	150 mm × 62 mm	7.0 ± 1.0%

accordance with the testing procedures specified in AASHTO T324. In Hamburg wheel tracking test, steel wheels, 1.85 in. wide with an 8-in. diameter, make 52 ± 2 passes across the specimen per minute. The load on each wheel is 158 ± 1.0 lb. Linear variable differential transformers (LVDTs) measure rut depth or deformation at 5 points along the length of each specimen.

6. Results and discussions

6.1. Dynamic modulus $|E^*|$

Fig. 1 shows the test results of $|E^*|$ for all SMA mixtures. It can be seen that all SMA mixtures had similar dynamic modulus at 4 and 20 °C, regardless of the load frequency, suggesting the incorporation of CRM into SMA mixtures had no significant effect on the dynamic modulus of SMA at low and medium temperatures. In addition, three rubberized SMA mixtures numerically exhibited higher dynamic modulus at 45 °C than virgin SMA, regardless of the load frequency. This indicates the incorporation of CRM improved the high temperature dynamic modulus of SMA mixes. For three introduction processes of CRM into SMA, dry process SMA showed lower dynamic modulus than other two rubberized SMAs and SBS SMA at 45 °C. This means dry process SMA may have lower resistance to deformation than the wet process, the terminal, and SBS SMA mixes. However, Tukey–Kramer statistical grouping ($\alpha = 0.05$) analysis indicated that no statistical differences in dynamic modulus of the five mixes, regardless of the temperature or load frequency.

6.2. Relaxation modulus ($E(t)$) and creep compliance ($D(t)$)

Once the $|E^*|$ values were obtained, relaxation modulus ($E(t)$) and creep compliance ($D(t)$) can be calculated using Eqs. (1) and (2), respectively [14]. Higher $E(t)$ and lower $D(t)$ represent the better resistance to rutting.

$$E(t) = E_\infty + \sum_{i=1}^{N} E_i e^{-t/\rho_i} \tag{1}$$

$$D(t) = D_0 + \sum_{i=1}^{N} D_i (1 - e^{-t/K_i}) \tag{2}$$

where E_∞ = elastic modulus, E_i = Prony coefficients, ρ_i = relaxation time, D_0, D_i = material constants, and K_i = retardation time of ith Voight element.

$E(t)$ and $D(t)$ master curves at 21 °C are shown for all SMA mixes in Figs. 2 and 3, respectively. It can be seen from Fig. 2 that dry process and wet process SMA mixes had similar $E(t)$ values, which were higher than that of virgin SMA while lower than those of terminal and SBS SMA mixes at longer loading times. Contrary trend was seen in $D(t)$ results. The terminal and SBS SMAs had the lowest $D(t)$, followed by wet process and dry process, and the virgin SMA had the highest $D(t)$ at longer loading times. This indicated that both dry process and wet process may improve the rutting resistance while their deformation resistance may be lower than terminal and SBS SMAs. This phenomenon may be attributed to the incorporation of SBS into both terminal and SBS SMAs.

6.3. Resistance to rutting/moisture

Fig. 4 presents the results from the Hamburg wheel-tracking test. The results indicated that the three introduction processes of CRM improved the rutting resistance of SMA. However, the wet process SMA exhibited much lower rutting depth than the dry process although both used the same CRM dosage, indicating the wet process may be a better approach than the dry process in improving the rutting resistance of SMA. Additionally, the terminal SMA had a higher rutting resistance than the dry process and wet process. This may be attributed to the use of combination of SBS and CRM in the terminal. Furthermore, the SBS SMA showed the best deformation resistance among the five SMA mixes.

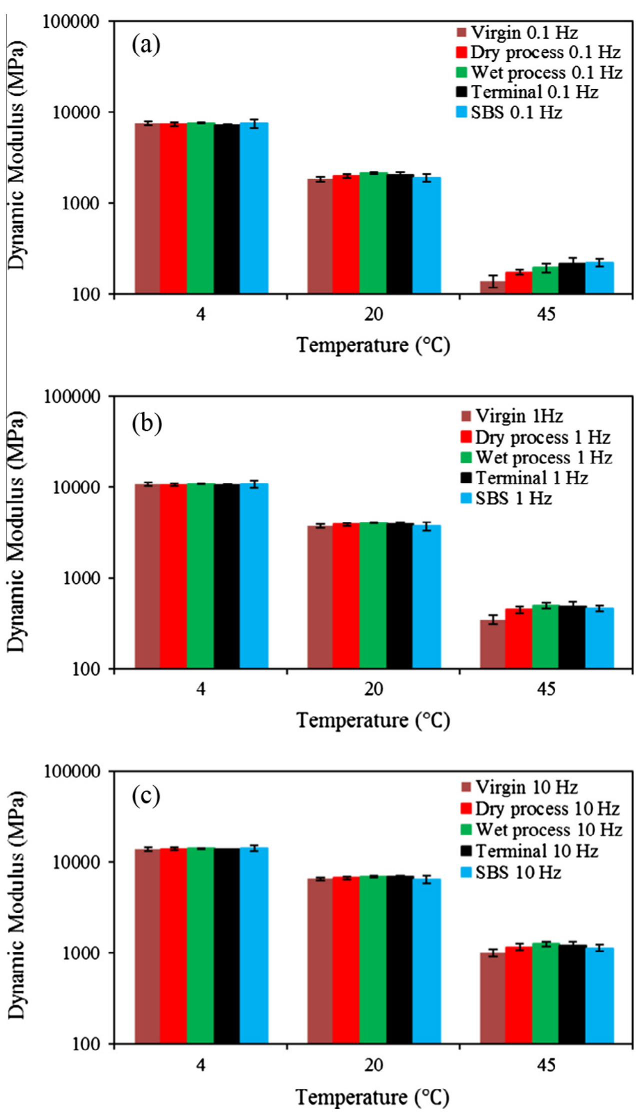

Fig. 1. Dynamic modulus vs. temperature at: (a) 0.1 Hz, (b) 1 Hz, and (c) 10 Hz.

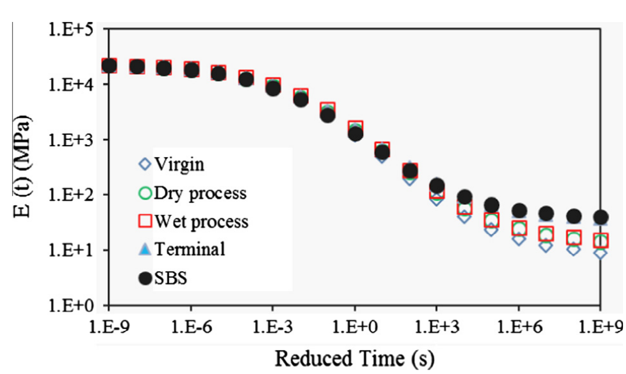

Fig. 2. Relaxation modulus ($E(t)$) master curves.

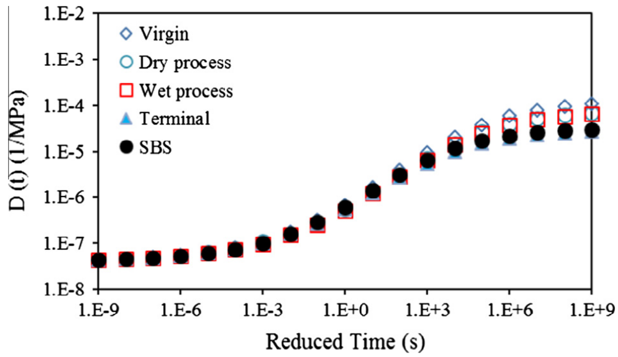

Fig. 3. Creep compliance ($D(t)$) master curves.

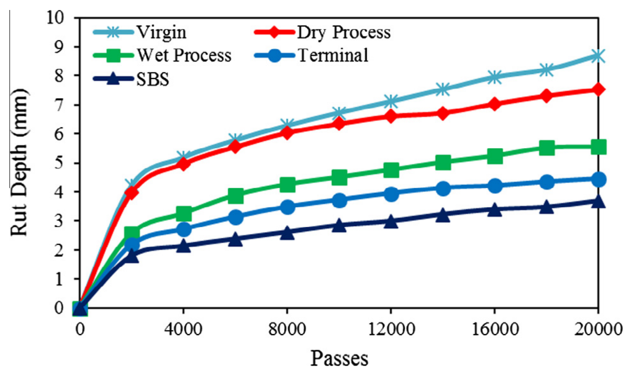

Fig. 4. Hamburg wheel-tracking test results.

It can be also found that no SMA exhibited a stripping inflection point after 20,000 wheel passes, which indicated no SMA mixes had significant moisture damage. This also suggested the incorporation of CRM and the introduction processes of CRM may have no significant effect on the moisture susceptibility.

6.4. Fatigue life of SMA mixture

The fatigue lives of five SMA mixes were predicted by S-VECD theory using direct tension fatigue test data. Fig. 5 presents the fatigue life of stress-controlled load at 25 °C and 10 Hz loading frequency. It can be seen that the dry process and wet process SMA mixes had similar the fatigue lives, which were higher than virgin SMA while lower than both terminal and SBS SMAs, regardless of the stress levels or the test temperatures. This suggests that the incorporation of CRM improved the fatigue life of SMA and the introduction methods of CRM (dry and wet process) had no significantly effect on the fatigue performance of SMAs. Additionally, the application of both SBS and CRM in the terminal SMA may result in a higher fatigue life. Furthermore, the fatigue lives of the dry process and wet SMAs were lower than that of SBS SMA, meaning 10% CRM could be not enough to make rubberized SMA life as long as SBS SMA.

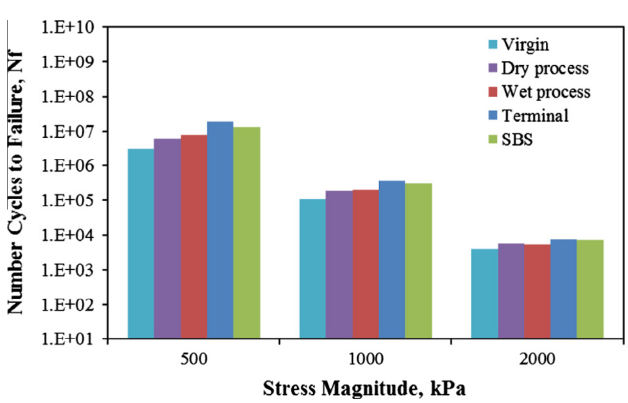

Fig. 5. Fatigue life.

7. Summary and conclusions

This paper investigated the performance of rubberized SMA mixes and compared their performance characterizes with SMA mixes with SBS modified binder and virgin binder. The performance properties evaluated included the dynamic modulus, rutting resistance, moisture susceptibility and fatigue resistance. The following conclusions may be offered based on the testing results:

(1) Numerically, rubberized SMA mixtures with 10% CRM of −30 mesh exhibited higher dynamic modulus at 45 °C, the resistance to rutting and fatigue cracking than virgin SMA. Tukey–Kramer statistical grouping ($\alpha = 0.05$) analysis indicated that no statistical differences in dynamic modulus between the five mixes, regardless of the temperature or load frequency.
(2) Dry process and wet process SMA mixes had similar $E(t)$ values, which were higher than that of virgin SMA while lower than those of terminal and SBS SMA mixes at longer loading times. Contrary trend was seen in $D(t)$ results. The same size and same amount of CRM, used in both dry process and wet process, could result in the similar values of $E(t)$ and $D(t)$.
(3) The wet process SMA in this study had the lower rutting than the dry process, while had the higher rutting than the terminal and SBS SMA.
(4) The introduction processes of CRM (dry process and wet process) may have no significant influence on the moisture susceptibility, when the 10% CRM of −30 mesh was used in both processes.
(5) Both dry process and wet process SMAs with 10% CRM of −30 mesh had the similar fatigue life, which, however, was lower than the terminal and SBS SMAs.

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